Wide-field Hard X-ray Survey with ART-XC

Chien-Ting Chen[1,2], Steven Ehlert[2], Doug Swartz[1,2]

[1]Science and Technology Institute, Universities Space Research Association, Huntsville, AL 35805, USA

[2]Astrophysics Office, NASA Marshall Space Flight Center, ZP12, Huntsville, AL 35812, USA

Abstract

The Mikhail Pavlinsky Astronomical Roentgen Telescope X-ray Concentrator (ART-XC) instrument onboard the Spectrum Röntgen Gamma (SRG) mission began the all-sky hard X-ray survey since December 2019 and has already completed the first two years of its planned four-year all sky survey. The observations of the ecliptic pole regions will reach exceptional depth thanks to the survey design of overlapping exposure in these regions. We discuss the progress of the ART-XC survey in the North Ecliptic Pole (NEP) region so far, including the status of the data reduction and analysis pipeline as well as the survey results.

Future Prospects

NASA MSFC, through a Partnership Agreement with the Russian Space Agency (IKI), is preparing the delivery of the survey data in a 200 deg^2 region centered at the North Ecliptic Pole (NEP). The current planned public data delivery date is March 2025, which is after the completion of the four-year all-sky survey. The software, documentation, and calibration database prepared by the MSFC ART-XC team will also be released with the data through HEASARC.

The ART-XC NEP field, with the wide 200 deg^2 area and a flux limit of reaching ~4x10^{-13} erg s^{-1} cm^{-2} after the first two years of the survey, will be the first hard X-ray blank field survey of this size and depth. The ART-XC NEP survey data will enable the community to make exciting scientific discoveries such as resolving the source population contributing to the peak of the Cosmic X-ray Background, understanding AGN demographics with an unbiased hard X-ray selected sample.

The Mikhail Pavlinsky ART-XC Telescope

The Mikhail Pavlinsky Astronomical Roentgen Telescope X-ray Concentrator (ART-XC), one of the two telescopes carried by the Spectrum Röntgen Gamma (SRG) observatory, is comprised of seven mirror modules (28 Ni/Co shells each) designed, fabricated and calibrated by MSFC. The illustrations of the SRG observatory and the ART-XC telescope are shown in Figure 1 and Figure 2-left.

ART-XC is capable of observing the 4-30 keV sky with with an angular resolution of FWHM~ 53" (pixel-size limited) and an energy resolution of 9%@13.9keV. The large field of view of (36' diameter) and effective area (385 cm^2@8.1 keV, all seven modules combined) make it a unique instrument for surveying the entire hard X-ray sky. A comparison between the effective area of the only two existing hard X-ray telescopes with focusing optics, ART-XC and NuSTAR, are shown in Figure 2-right. The in-flight performance of the ART-XC spectral and imaging capabilities are shown in Figure 3.

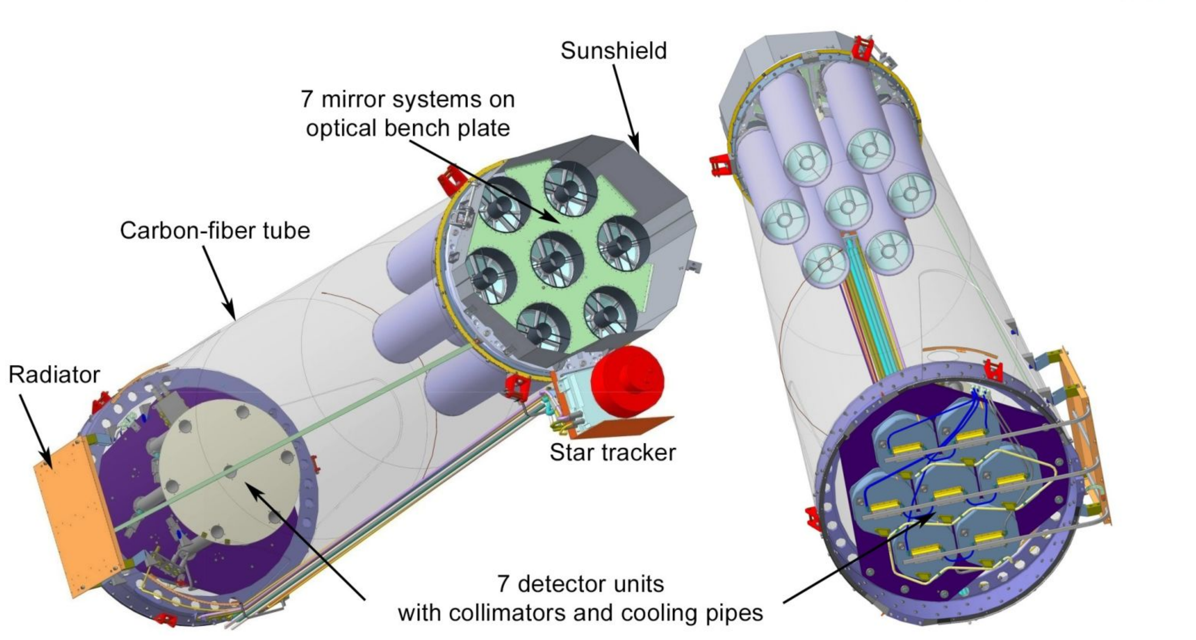

Figure 1: Schematic of ART-XC instrument showing the array of 7 co-aligned mirror modules, sunshield, and star tracking camera at one end of the carbon-fiber optical bench and the matching array of 7 detectors, collimators and passive thermal control at the other end of the optical bench.

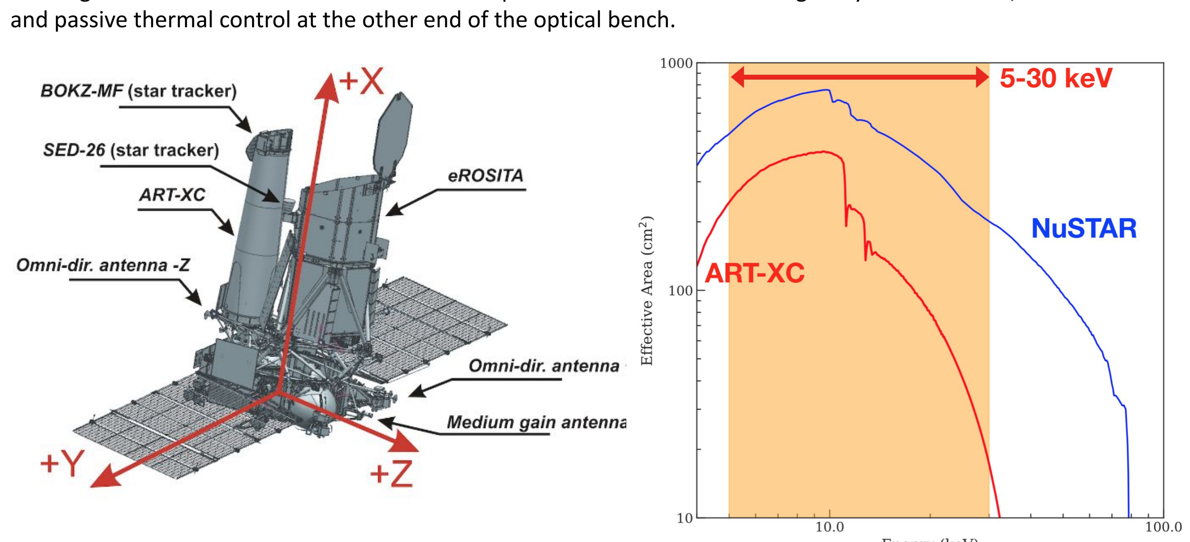

Figure 2: Left - Schematic of SRG mission indicating major components related to the ART-XC instrument including locations of starc tracking cameras and communication antennae. Image credit: Sunyaev et al. (2021).

Right - A comparison between the effective area of ART-XC (all seven modules combined) and NuSTAR (two focal plane modules combined).

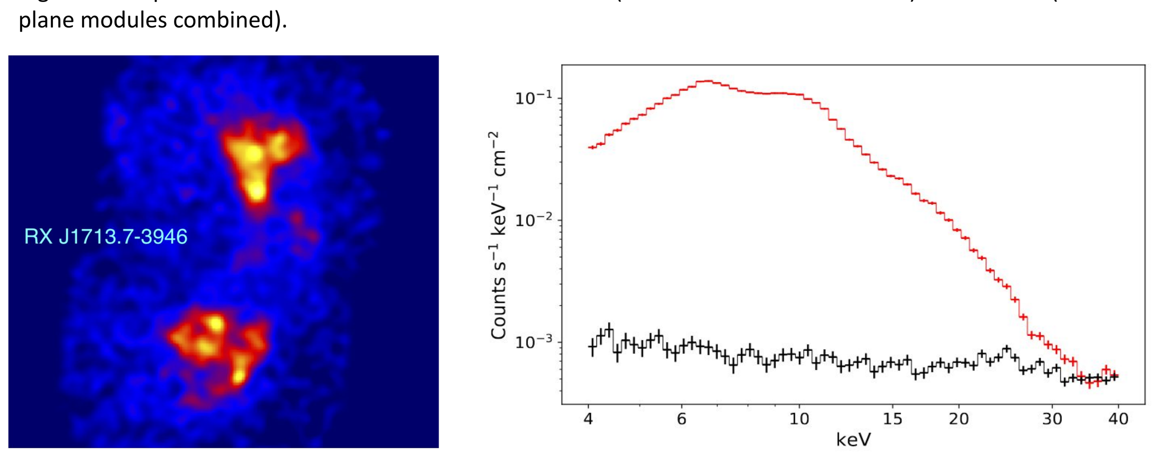

Figure 3: Left- 40' by 40' ART-XC 4-12 keV image from a CalPV phase observation for a supernova remnant RX J1713.7−3946, which shows the resolved hard X-ray structure. Image credit: Sunyaev et al. (2021).

Right - Raw detector spectrum from a 20 ks CalPV observation of the bright Galactic high mass X-ray binary OAO 1657−415. The source spectrum is shown in red while the background spectrum is shown in black. This demonstrates the spectral capability of ART-XC up to ~ 30 keV (image credit: Pavlinsky et al. 2021a)

The 1-year ART-XC all-sky survey catalog

ART-XC is conducting a survey that scans the entire sky every six months. The sources detected in the first-year all-sky survey (two scans) were recently published in Pavlinsky et al. (2021b). Here we briefly summarize the results of the first-year catalog. A total of 867 sources were included in the catalog. A total of 750 sources have a known counterpart with ~56% of them being extragalactic . The sensitivity of the survey is ~ 4x10^{-12} erg s^{-1}cm^{-2} in the ecliptic plane and ~ 8x10^{-13} erg s^{-1}cm^{-2} in the ecliptic poles. We show the positions of the full first-year catalog in Figure 4, the cumulative 4-12 keV flux distribution in Figure 5-left, and the 4-12 keV image for one of the detected sources. We refer the readers to Pavlinsky et al. (2021b) for the details of the source catalog.

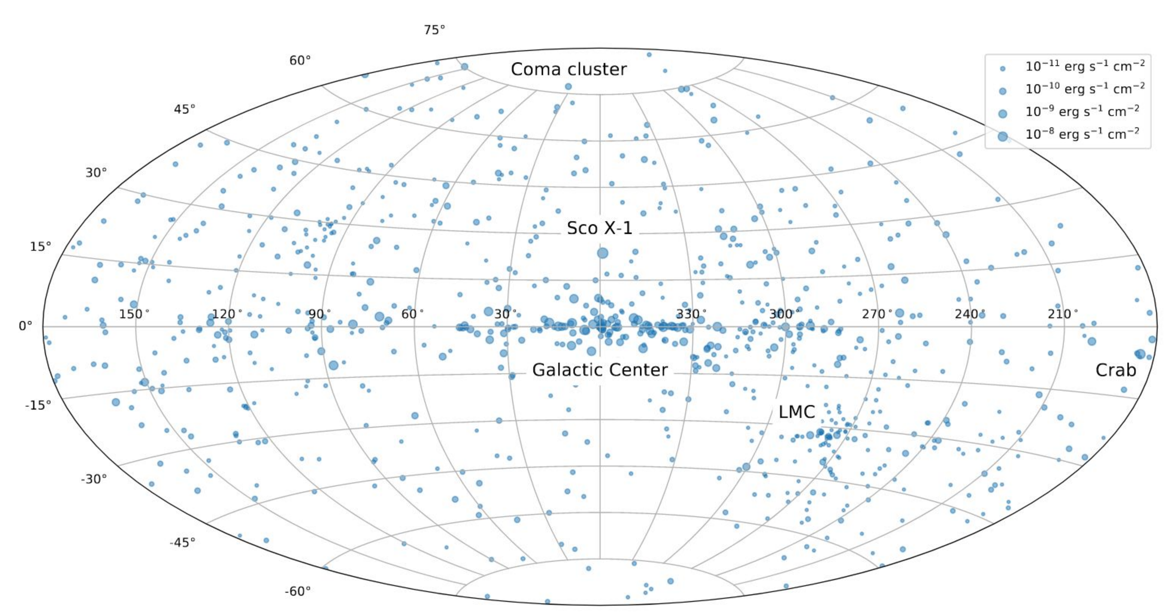

Figure 4 - Positions (in Galactic coordinates) of the X-ray sources detected by ART-XC in the 4–12 keV energy band during the first year of the all-sky survey. The symbol size reflects the X-ray brightness of a source, as indicated in the legend in the top right corner. Adopted from Pavlinsky et al. (2021b).

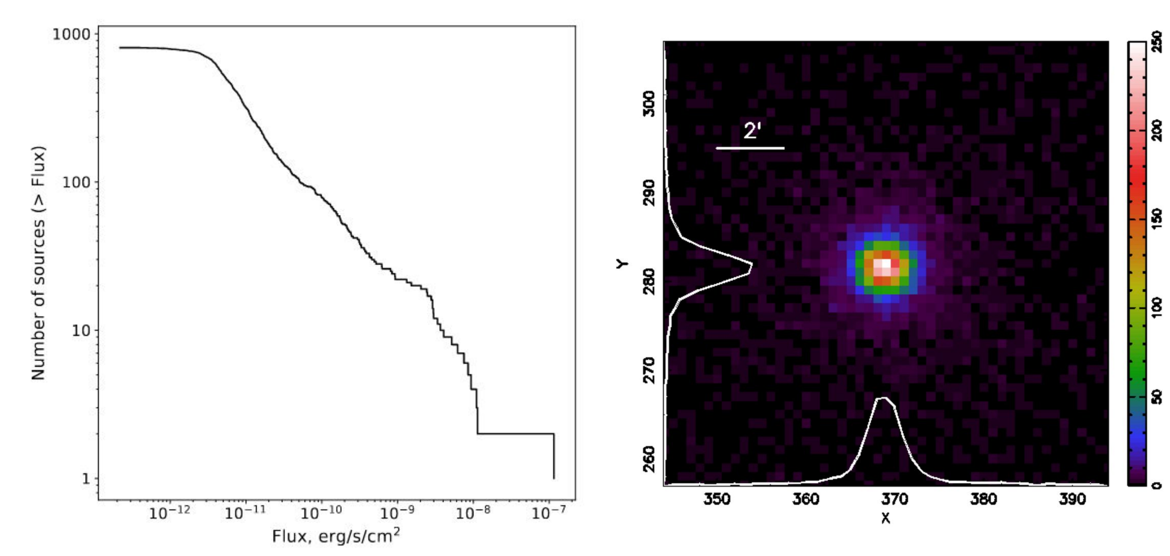

Figure 5: Left - Cumulative flux distribution of the ART-XC all-sky catalog from Pavlinsky et al. (2021b).

Right - An example of a source detected in the ART-XC all-sky survey, V1101 Sco (a Swift/BAT low-mass X-ray binary). The image shown here is constructed based on events from all seven mirror modules, with no apparent astrometry offsets between individual mirror modules, and a PSF FWHM of ~50" and astrometry accuracy of 1.5".

The ART-XC NEP Survey

Hard X-ray observatories can probe > 10 keV photons that can penetrate through thick obscuring column densities. Extragalactic surveys with these instruments are ideal for studying the hard X-ray sources unbiased by intervening dust (most of which are active galactic nuclei or X-ray binaries), and thus resolving the sources that contribute to the > 10 keV peak of the Cosmic X-ray Background. The orbit and rotation orientation of SRG during the all-sky survey guarantees the ecliptic pole regions is sampled ≈ 4× deeper than the average sky position. The deep sensitivity limit and the wide area make the ART-XC NEP field a unique addition to existing > 10 keV surveys (Figure 6-left). Despite a small patch of the sky (a few ART-XC FOV) that ART-XC revisits every ~4 hours, the ART-XC NEP survey is a relatively homogeneous survey (Figure 6-right) and will enable studies requiring such surveys such as resolving the Cosmic X-ray Background and X-ray luminosity function measurements.

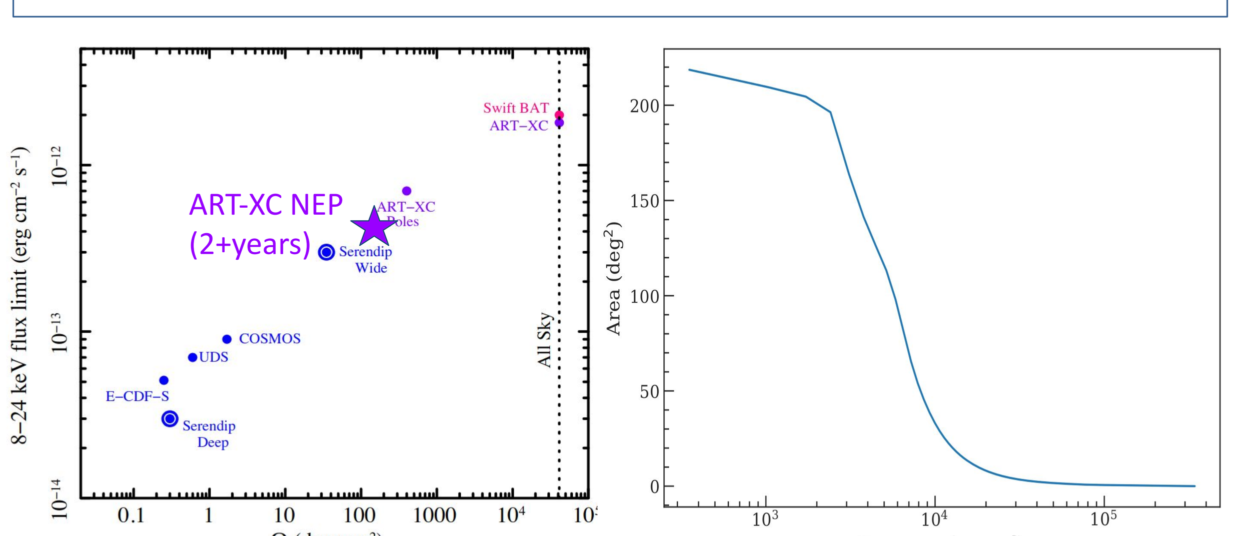

Figure 6: Left - Flux limit vs. solid angle of sky coverage for 8–24 keV surveys from Swift/BAT (red), NuSTAR (blue), and SRG ART-XC (purple) adopted from Brandt & Yang (2021). The additional large purple star marks the increased sensitivity limits in NEP as the ART-XC survey completes its 2nd year survey.

Right - Cumulative survey solid angle versus exposure time for the ART-XC NEP survey. The small area with > 10^5 second corresponds to the axis of ART-XC's survey pattern on the ecliptic plane.

ART-XC NEP source properties

The first year catalog includes 17 sources in the NEP region. The number increases to ~40 after incorporating the data from the second year. We investigate the multiwavelength properties of these ART-XC NEP sources by matching them to archival optical and IR catalogs, including Pan-STARRS DR2, WISE, 2MASS, and SDSS. We also match the sources to archival X-ray catalogs from Chandra, XMM, NuSTAR, ROSAT, and Swift. The majority of the NEP sources are AGN, as expected given the flux limit of the survey and the high galactic latitude of the field. For the sources with archival redshift measurements, we show the hard X-ray luminosity (shifted to rest-frame 10-40 keV assuming a Galactic absorption and a simple power-law spectrum with a photon index of 1.8.) of the ART-XC NEP sources in Figure 9-left. For sources with a soft X-ray counterpart in the literature, we study their ``hardness ratio'' ((H-S)/(H+S)) by making use of the soft X-ray fluxes from 0.5-4 keV as the "soft band, S" and the 4-12 keV ART-XC flux as the "hard band, H". We show the hardness ratio distribution of these sources in Figure 9-right. Our preliminary analysis of the ART-XC NEP sources suggest that the source in the ART-XC NEP survey is a unique hard X-ray selected sample not covered current hard X-ray surveys such as those from Swift/BAT and NuSTAR. The hardness ratio distribution span a wide range, suggesting that ART-XC selected sample does provide an unbiased view for both the obscured and unobscured sources.

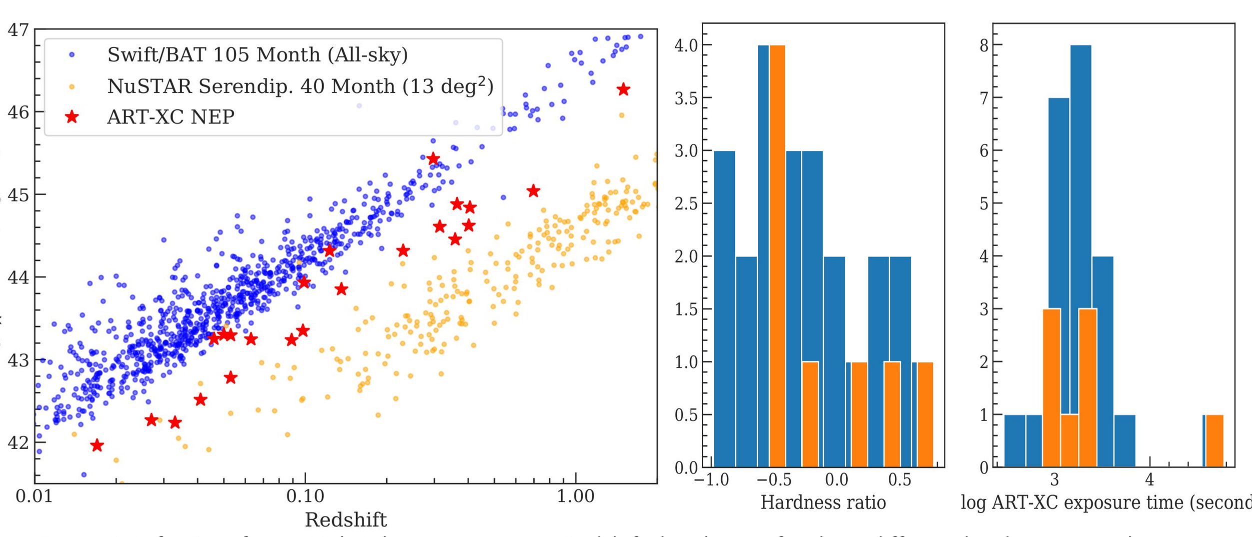

Figure 9: Left - Rest-frame 10-keV luminosity versus Redshift distribution for three different hard X-ray samples selected from blank-field surveys, including Swift/BAT (blue, the 105-month catalog by Oh et al. 2018), NuSTAR (yellow, the Serendipitous Survey by Lansbury et al. 2017), and ART-XC NEP (2-year).

Right - The Hardness ratio and exposure time distributions of the ART-XC NEP sources found to have a soft X-ray counterpart from Chandra, XMM-Newton, Swift/XRT, or ROSAT. The hardness ratios were calculated using (H-S)/(H+S), where S is the soft-band flux in 0.5-4 keV (homogenized assuming a simple absorbed Γ=1.8 power-law) and H is the 4-12 keV hard-band flux from ART-XC. A fraction of the ART-XC NEP sources are also detected in the Swift/BAT catalog, their hardness ratios are shown as the orange histograms.

Source Searching and Background Characterization

The sensitivity of the ART-XC NEP survey is largely dependent to the particle background intensity at the L2 orbit, which is relatively high (Figure 10-left, see Pavlinsky et al. 2021). The background and the constant movement of the ART-XC telescope make traditional source finding and background estimation efforts challenging. Therefore, the sources in the ART-XC all-sky and NEP catalogs are detected using the probability map generated by convolving the event lists with an optimal filter considering the background, the telescope PSF, and vignetting functions (Pavlinsky et al. 2021):

$$\Phi(x) = \ln\left(\frac{f(e)v(x,e)}{b(x,e)}P(x_0|x)+1\right)$$

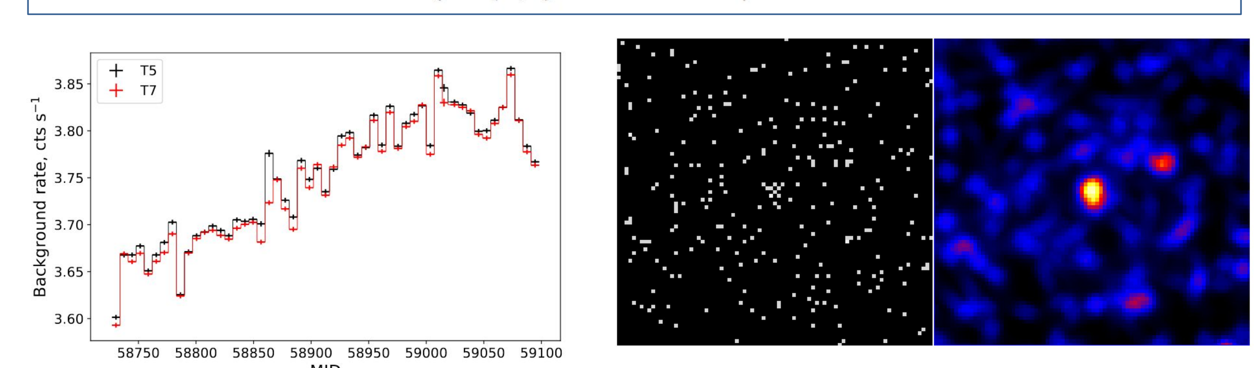

Figure 8: Left - Weekly-averaged event count rate in the 40-100 keV band, which is dominated by the particle background. Two of the seven telescope modules are shown. Right - Example of a detection of a faint source using the events convolved with the optimal filter. The left panel is the raw photon image in the 4-12 keV band and the right panel shows the optimal filter convolved probability map. The size of the images is ~ 20'x20'. Image credit: Pavlinsky et al. 2021a.

Acknowledgement

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The ART-XC Data Calibration and Analysis

The MSFC ART-XC team is currently developing the calibration database and data analysis software. The calibration efforts include ground-based observations using MSFC's Stray Light Test Facility and space-based observations (Figure 7 and 8). The wide field-of-view (FOV), high angular-resolution, and the hard (5-30 keV) energy range, as demonstrated by the in-flight performance verification observations (CalPV) shown in Figure 3 to the left, and Figure 7 below, ensure the completed 4-year ART-XC NEP survey to provide the necessary survey volume and depth to advance our understanding of the hard X-ray Universe.

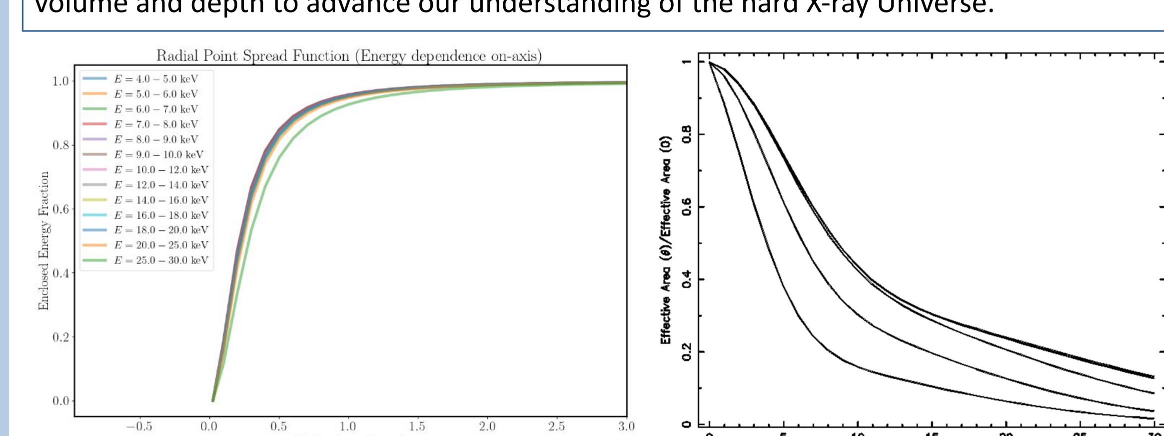

Figure 6: Left - Encircled energy fraction measurements based on calibration data taken at MSFC's Stray Light Test Facility (SLTF). The ~30" half-power diameter of the ART-XC mirror modules provide the necessary spatial resolution to focus on faint hard X-ray sources. Right - Azimuthally-averaged effective area as a function of off-axis angle, θ, normalized to the on-axis value, for several representative energies; 4, 6, 8, 12, and 20 keV from top to bottom.

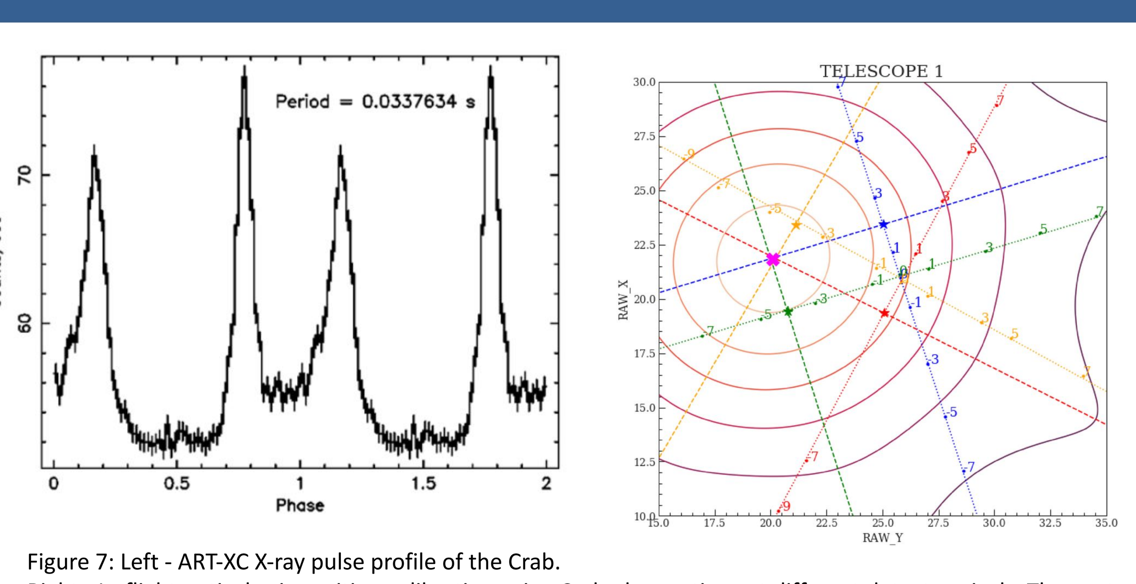

Figure 7: Left - ART-XC X-ray pulse profile of the Crab.

Right - In-flight optical axis position calibration using Crab observations at different detector pixels. The contours are the probability density function of the optical axis position based on the vignetting profile of Crab observations at different position on the detector.

Contact

Chien-Ting Chen
chien-ting.chen@nasa.gov

References

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2. Pavlinsky et al. 2021b
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